

# Higgs singlet boson as a diphoton resonance in a vector-like quark model

R. Benbrik <sup>\*,1,2</sup> Chuan-Hung Chen <sup>†,3</sup> and Takaaki Nomura <sup>‡4</sup>

<sup>1</sup>*LPHEA, Semlalia, Cadi Ayyad University, Marrakech, Morocco*

<sup>2</sup>*MSISM Team, Faculté Polydisciplinaire de Safi,  
Sidi Bouzid B.P 4162, 46000 Safi, Morocco*

<sup>3</sup>*Department of Physics, National Cheng-Kung University, Tainan 70101, Taiwan*

<sup>4</sup>*School of Physics, Korea Institute for Advanced Study, Seoul 130-722, Republic of Korea*

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## Abstract

ATLAS and CMS recently show the first results from run 2 of the Large Hadron Collider (LHC) at  $\sqrt{s} = 13$  TeV. A resonant bump at a mass of around 750 GeV in the diphoton invariant mass spectrum is indicated and the corresponding diphoton production cross section is around 3-10 fb. Motivated by the LHC diphoton excess, we propose that the possible resonance candidate is a Higgs singlet. To produce the Higgs singlet via gluon-gluon fusion process, we embed the Higgs singlet in the framework of vector-like triplet quark (VLTQ) model. As a result, the Higgs singlet decaying to diphoton final state is via VLTQ loops. Using the enhanced number of new quarks and new Yukawa couplings of the VLTQs and Higgs singlet, we successfully explain the diphoton production cross section. We find that the width of the Higgs singlet is below 1 GeV, its production cross section can be of order of 1 pb at  $\sqrt{s} = 13$  TeV, and the branching ratio for it decaying to diphoton is around 0.017 and is insensitive to the masses of VLTQs and new Yukawa couplings. We find a strong correlation between the Higgs Yukawa couplings to  $s$ - $b$  and  $c$ - $t$ ; the resulted branching ratio for  $t \rightarrow ch$  can be  $1.1 \times 10^{-4}$  when the constraint from  $B_s$  oscillation is applied. With the constrained parameter values, the signal strength for the SM Higgs decaying to diphoton is  $\mu_{\gamma\gamma} < 1.18$ , which is consistent with the current measurements at ATLAS and CMS.

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\* Email: rbenbrik@ictp.it

† Email: physchen@mail.ncku.edu.tw

‡ Email: nomura@kias.re.kr

## I. INTRODUCTION

A scalar resonance with a mass of around 125 GeV was first discovered in the diphoton invariant mass spectrum and four-lepton channel at the ATLAS [1] and CMS [2] experiments. The scalar particle is identified as the Higgs boson which is responsible for the electroweak symmetry breaking (EWSB) in the standard model (SM).

With  $\sqrt{s} = 13$  TeV, ATLAS and CMS recently report the first results from run 2 of the Large Hadron Collider (LHC) and both experiments show a moderate bump at around 750 GeV in the diphoton invariant mass spectrum, where ATLAS (CMS) employs  $3.2(2.6)$  fb $^{-1}$  of data [3, 4]. With the narrow width approximation, the ATLAS and CMS experiments show that the local significances for the diphoton excess are  $3.6\sigma$  and  $2.6\sigma$  while the global significances are  $2.0\sigma$  and  $1.2\sigma$ , respectively.

The earlier search for diphoton resonances was performed by ATLAS [5] and CMS [6] at  $\sqrt{s} = 8$  TeV. Although ATLAS found nothing exotic events, CMS indicated some excess at the diphoton invariant mass of around 750 GeV. Combined with the earlier diphoton excess, the local (global) significance at the CMS becomes  $3.0(1.7)\sigma$ . Motivated by the intriguing diphoton excess, the resonance candidates are proposed [7–45].

Taking the CMS combined results as an illustration, if a resonance at 750 GeV exists, the cross section for the process  $pp \rightarrow X \rightarrow \gamma\gamma$  should be around 3-10 fb, where  $X$  denotes the unknown resonance. If we assume that the resonance is a scalar and its couplings to the SM fermions and gauge bosons are similar to the SM Higgs, one can see that the production cross section times the branching ratio (BR) for  $X \rightarrow \gamma\gamma$  decay is  $\sigma(pp \rightarrow X) \cdot BR(X \rightarrow \gamma\gamma) \approx 1.33 \times 10^{-4}$  fb at  $\sqrt{s} = 13$  TeV [63]. The diphoton production cross section is too small to explain the excess. Therefore, if the resonance is a scalar boson, the main problem is that  $BR(X \rightarrow \gamma\gamma)$  should be of order of  $10^{-3}$  when  $\sigma(pp \rightarrow X)$  is around 1 pb.

Since the heavy scalar or pseudoscalar boson in an ordinary two-Higgs-doublet model (2HDM) can couple to the weak gauge bosons and/or the SM fermions at the tree level, it may be difficult to escape the problem of small  $BR(X \rightarrow \gamma\gamma)$ . To avoid this small BR, we propose that the new resonance candidate is a Higgs singlet ( $S$ ) in which it does not couple to the gauge bosons and the SM fermions at the tree level. In order to produce this singlet by gluon-gluon fusion (ggF) process, we introduce new exotic quarks with masses of 1 TeV to couple to the Higgs singlet.

The proposal is motivated from the loop induced effective interaction of the SM Higgs coupling to gluons, expressed as [64–67]:

$$\mathcal{L}_{hgg} = \frac{\alpha_s}{12\pi} \frac{y_t}{\sqrt{2}m_t} n_F h G_{\mu\nu}^a G^{a\mu\nu}, \quad (1)$$

where  $y_t$  is the top-quark Yukawa coupling,  $v$  is the vacuum expectation value (VEV) of the SM Higgs, the mass of top quark is determined by  $m_t = y_t v / \sqrt{2}$ ,  $n_F$  is the number of possible heavy quarks in the loop, and  $n_F = 1$  in the SM. From Eq. (1), it can be seen that the  $h$  production cross section by ggF process can be enhanced by the Yukawa coupling and the number of heavy quarks. For illustration, if we pretend  $n_F = y_t = 3$ ,  $m_t = 1$  TeV and  $m_h = 750$  GeV, the  $h$  production cross section can reach  $\mathcal{O}(1)$  pb. That is, the production cross section for the proposed Higgs singlet can easily reach the level of pb when the number of new exotic quarks and Yukawa coupling are taken properly. Since the Higgs singlet can only decay via the new quark loops in which  $S \rightarrow gg$  is the dominant decay channel; therefore, the BR for the  $S$  decaying to diphoton can be naively estimated by  $\Gamma(S \rightarrow \gamma\gamma)/\Gamma(S \rightarrow gg) \sim 32/256 Q_F^4 N_c^2/n_F^2 \alpha^2/\alpha_s^2 \approx 3.0 \times 10^{-3}$ , where  $Q_F^2$  is the sum of squared electric charges of new quarks inside loop and we take  $Q_F^2 = 2$  and  $n_F = 3$  as the example. Clearly, the resulted  $\sigma(pp \rightarrow S \rightarrow \gamma\gamma)$  can match with the measurements from the LHC run 2.

In order to establish a model that obeys the SM gauge symmetry, is anomaly free, possesses a scalar with a mass of around 750 GeV, and naturally provides larger  $n_F$  and Yukawa couplings, we investigate the subject in the framework of vector-like quark (VLQ) model with a heavy  $SU(2)_L$  Higgs singlet. The related studies with Higgs singlet and/or VLQs for explaining the diphoton excess can be referred to [10, 12, 13, 15, 18, 19, 25, 28, 29, 43]. From a fundamental theoretical perspective, which is for resolving hierarchy issue, matter-antimatter asymmetry, etc, the VLQs are predicted by the theories, such as Little Higgs models [46–49], composite Higgs models [50–54], extra dimensions [55, 56], and nonminimal supersymmetric SM [57–62]. A Higgs singlet can be also embedded in these models. For phenomenological study, we directly add the VLQs and a Higgs singlet to the SM.

Basically, there is no limit for the possible representations of VLQs. If we consider the VLQs those which can only mix with the SM up or down type quarks, the possible representations are singlet, doublet, and triplet [68–76]. To avoid introducing too many VLQ states, we adopt the vector-like triplet quarks (VLTQs) in which each triplet has three

new quarks. In the base of gauge eigenstates, the introduced Higgs singlet only couples to VLTQs.

Since the introduced VLQs have different isospins from the SM quarks, therefore, the Higgs- and  $Z$ -mediated flavor changing neutral currents (FCNCs) occur at the tree level. Due to the new Yukawa couplings to VLQs and the SM quarks, besides the SM Higgs coupling to top-quark is modified, the SM Higgs couplings to VLQs are also induced. The SM Higgs production cross section and its decay to diphoton thus are changed. It is interesting to see the influence of the model on the Higgs measurements and its implications at the LHC.

The paper is organized as follows. In Sec. II, we briefly introduce the model and present the new scalar potential, new Yukawa couplings, and new gauge couplings to the introduced vector-like quarks. We study the properties of Higgs singlet and discuss its production and various decays in Sec. III. In the same section, we also investigate the implications of new effects on the SM Higgs decay to diphoton, top FCNCs, and collider signatures. We give the conclusion in Sec. IV.

## II. MODEL

We extend the SM by including one real Higgs singlet  $S$  and two VLTQs, where the representations of VLTQs in  $SU(3)_c \times SU(2)_L \times U(1)_Y$  gauge symmetry are chosen as  $(3, 3)_{2/3}$  and  $(3, 3)_{-1/3}$  [69]. Since the current Higgs measurements give a strict bound on the mixing angle between  $S$  and the SM Higgs [76], in order to suppress the mixing effect at the tree level, we impose a  $Z_2$  discrete symmetry to the  $S$  field, that is,  $S \rightarrow -S$  under the  $Z_2$  transformation. The scalar potential, obeyed the SM gauge symmetry and  $Z_2$  symmetry, is expressed as:

$$V(H, S) = \mu^2 H^\dagger H + \lambda_1 (H^\dagger H)^2 + m_S^2 S^2 + \lambda_2 S^4 + \lambda_3 S^2 (H^\dagger H). \quad (2)$$

The representation of SM Higgs doublet is taken as:

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix}, \quad (3)$$

where  $G^+$  and  $G^0$  are Goldstone bosons,  $h$  is the SM Higgs field and  $v$  is the VEV of  $H$ . The scalar potential in Eq. (2) can not develop a non-vanished VEV for  $S$  field when  $\lambda_{2,3} > 0$ . Thus, like the SM,  $v = \sqrt{-\mu^2/\lambda_1}$  and  $m_h = \sqrt{2\lambda_1}v \approx 125$  GeV. Due to the  $Z_2$  symmetry,

$h$  and  $S$  do not mix at the tree level and  $m_S$  is the mass of  $S$ . We note that the  $Z_2$  can be softly broken by the mass terms of VLTQs.

The gauge invariant Yukawa couplings of VLTQs to the SM quarks, the SM Higgs doublet, and the new Higgs singlet are written as:

$$\begin{aligned}
-\mathcal{L}_{\text{VLTQ}}^Y = & \bar{Q}_L \mathbf{Y}_1 F_{1R} \tilde{H} + \bar{Q}_L \mathbf{Y}_2 F_{2R} H + y_1 \text{Tr}(\bar{F}_{1L} F_{1R}) S + y_2 \text{Tr}(\bar{F}_{2L} F_{2R}) S \\
& + M_{F_1} \text{Tr}(\bar{F}_{1L} F_{1R}) + M_{F_2} \text{Tr}(\bar{F}_{2L} F_{2R}) + h.c.,
\end{aligned} \tag{4}$$

where  $Q_L$  is the left-handed SM quark doublet and regarded as mass eigenstate before the VLTQs are introduced, all flavor indices are hidden,  $\tilde{H} = i\tau_2 H^*$ , and  $F_{1(2)}$  is the  $2 \times 2$  VLTQ with hypercharge  $2/3(-1/3)$ . To keep the dimension-4 operator terms, we require that  $F_{1L,2L}$  carry the  $Z_2$  charge; the representations of  $F_{1,2}$  in  $SU(2)_L$  are expressed by:

$$F_1 = \begin{pmatrix} U_1/\sqrt{2} & X \\ D_1 & -U_1/\sqrt{2} \end{pmatrix}, \quad F_2 = \begin{pmatrix} D_2/\sqrt{2} & U_2 \\ Y & -D_2/\sqrt{2} \end{pmatrix}. \tag{5}$$

The electric charges of  $U_{1,2}$ ,  $D_{1,2}$ ,  $X$  and  $Y$  are  $2/3$ ,  $-1/3$ ,  $5/3$  and  $-4/3$ , respectively. Therefore,  $U_{1,2}(D_{1,2})$  can mix with up (down) type SM quarks. The masses of VLTQs do not originate from the electroweak symmetry breaking. Due to the gauge symmetry, the VLTQs in the same multiplet state are degenerate and denoted by  $M_{F_{1(2)}}$ . Since the mass terms of VLTQs do not involve  $S$  field and the associated operators are dimension-3, therefore, the discrete  $Z_2$  is softly broken by  $M_{F_{1,2}}$  terms.

Since the  $S$  field is a  $SU(2)_L$  singlet, it can not directly couple to weak gauge bosons; however, the effective couplings to these gauge bosons can be induced through the VLTQ loops. Thus, it is necessary to study the weak interactions of VLTQs. We write the covariant derivative of  $SU(2)_L \times U(1)_Y$  as:

$$D_\mu = \partial_\mu + i \frac{g}{\sqrt{2}} (T^+ W_\mu^+ + T^- W_\mu^-) + i \frac{g}{c_W} (T_3 - s_W^2 Q) Z_\mu + ie Q A_\mu, \tag{6}$$

where  $W_\mu^\pm$ ,  $Z_\mu$  and  $A_\mu$  stand for the gauge bosons in the SM,  $g$  is the gauge coupling of  $SU(2)_L$ ,  $s_W(c_W) = \sin \theta_W(\cos \theta_W)$ ,  $\theta_W$  is the Weinberg angle,  $T^\pm = T_1 \pm iT_2$ , and the charge operator  $Q = T_3 + Y$  with that  $Y$  is the hypercharge of particle. The generators of  $SU(2)_L$  in triplet representation are set to be:

$$T_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \quad T_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & -i & 0 \\ i & 0 & -i \\ 0 & i & 0 \end{pmatrix}, \quad T_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}. \tag{7}$$

Accordingly, the gauge interactions of new quarks are summarized as:

$$\begin{aligned} \mathcal{L}_{VFF} = & -g \left[ (\bar{X}\gamma^\mu U_1 + \bar{U}_1\gamma^\mu D_1 + \bar{D}_2\gamma^\mu Y + \bar{U}_2\gamma^\mu D_2) W_\mu^+ + h.c. \right] \\ & - \left[ \frac{g}{c_W} \bar{F}_1 (T^3 - s_W^2 Q_1) F_1 Z_\mu + e \bar{F}_1 \gamma^\mu Q_1 F_1 A_\mu + (F_1 \rightarrow F_2, Q_1 \rightarrow Q_2) \right], \end{aligned} \quad (8)$$

where the alternative expressions for the VLTQs are given by  $F_1^T = (X, U_1, D_1)$  and  $F_2^T = (U_2, D_2, Y)$  and the associated charge operators are  $\text{diag} Q_1 = (5/3, 2/3, -1/3)$  and  $\text{diag} Q_2 = (2/3, -1/3, -4/3)$ . Since the left-handed and right-handed VLTQs have the same couplings to the gauge bosons, therefore, the vector-like quarks in Eq. (8) are not separated by their chirality.

### III. PHENOMENA OF THE HIGGS SINGLET, THE SM HIGGS, AND THE VLQS

#### A. Decays and production of the Higgs singlet

After introducing the model, we analyze the production and decays of  $S$  at 13 TeV LHC. Since the  $S$  mainly couples to the VLTQs, its production is through one-loop ggF process. Thus, the effective coupling induced from the VLTQ loops for  $Sgg$  is formulated by:

$$\mathcal{L}_{Sgg} = \frac{\alpha_s}{8\pi} \left( \sum_{i=1,2} \frac{n_{F_i} y_i}{2m_{F_i}} A_{1/2}(\tau_i) \right) S G^{a\mu\nu} G_{\mu\nu}^a, \quad (9)$$

where  $n_{F_i} = 3$  is the number of VLTQs in the triplet state  $F_i$  and the loop function is

$$A_{1/2}(\tau) = 2\tau[1 + (1 - \tau)f(\tau)^2] \quad (10)$$

with  $\tau = 4m_F^2/m_S^2$  and  $f(x) = \sin^{-1}(1/\sqrt{x})$ . Accordingly, the partial decay width for  $S \rightarrow gg$  is derived by:

$$\Gamma(S \rightarrow gg) = \frac{\alpha_s^2 m_S^3}{32\pi^3} \left| \sum_{i=1,2} \frac{n_{F_i} y_i}{2m_{F_i}} A_{1/2}(\tau_i) \right|^2. \quad (11)$$

With the electromagnetic interactions in Eq. (8), the partial decay width via the VLTQ loops for  $S \rightarrow \gamma\gamma$  is obtained as [76]:

$$\Gamma(S \rightarrow \gamma\gamma) = \frac{\alpha^2 m_S^3}{256\pi^3} \left| \sum_i \frac{y_i Q_{F_i}^2 N_c}{m_{F_i}} A_{1/2}(\tau_i) \right|^2, \quad (12)$$

where  $N_c = 3$  is the number of colors and  $Q_{F_i}$  stands for the total electric charge of triplet  $F_i$ . The partial decay width for  $S \rightarrow Z\gamma$  can be formulated as:

$$\begin{aligned}\Gamma(S \rightarrow Z\gamma) &= \frac{N_c^2 m_S^3}{32\pi} |A_F|^2 \left(1 - \frac{m_Z^2}{m_S^2}\right)^3, \\ A_F &= \frac{\alpha}{2\pi s_W c_W} \sum_{i, f_i} \frac{-4y_i Q_{f_i}}{m_{F_i}} (T_{f_i}^3 - s_W^2 Q_{f_i}) [I_1(\tau_{f_i}, \lambda_{f_i}) - I_2(\tau_{f_i}, \lambda_{f_i})],\end{aligned}\quad (13)$$

where  $i = 1, 2$ ,  $f_i$  is the possible VLQ in  $F_i$ ,  $\tau_{f_i} = 4m_{F_i}^2/m_S^2$ ,  $\lambda_{f_i} = 4m_{F_i}^2/m_S^2$ , the summation is for  $i$  and  $f_i$ , and the loop integrals are given as [64]:

$$\begin{aligned}I_1(a, b) &= \frac{ab}{2(a-b)} + \frac{a^2 b^2}{2(a-b)^2} [f(a)^2 - f(b)^2] + \frac{a^2 b}{(a-b)^2} [g(a) - g(b)], \\ I_2(a, b) &= -\frac{ab}{2(a-b)} [f(a)^2 - f(b)^2], \\ g(t) &= \sqrt{t-1} \sin^{-1}(1/\sqrt{t}).\end{aligned}\quad (14)$$

In order to calculate the loop-induced  $S \rightarrow W^+W^-/ZZ$  decays, we ignore the small effect from  $m_{W(Z)}^2/m_S^2$  and the decay widths are derived as:

$$\begin{aligned}\Gamma(S \rightarrow W^+W^-) &= \frac{\alpha^2 m_S^3}{256\pi^3} \left| \sum_{i=1,2} \frac{2y_i N_c}{m_{F_i} s_W^2} A_{1/2}(\tau_i) \right|^2, \\ \Gamma(S \rightarrow ZZ) &= \frac{\alpha^2 m_S^3}{256\pi^3} \left| \sum_{i, f_i} \frac{y_i N_c (T_{f_i}^3 - s_W^2 Q_{f_i})^2}{m_{F_i} s_W^2 c_W^2} A_{1/2}(\tau_i) \right|^2.\end{aligned}\quad (15)$$

Since  $Z_2$  is broken by the mass terms of VLTQs,  $S \rightarrow hh$  decay can be induced at the loop level. The partial decay width is obtained as:

$$\begin{aligned}\Gamma(S \rightarrow hh) &= \frac{m_S}{16\pi} \lambda_{Shh}^2 \sqrt{1 - \frac{4m_h^2}{m_S^2}}, \\ \lambda_{Shh} &= \frac{2N_c y}{(4\pi)^2} \sum_i \left[ \frac{3m_S (Y_{i2}^2 + Y_{i3}^2)}{4m_{F_i}} I(m_S^2/m_{F_i}^2) \right], \\ I(z) &= \int_0^1 dx_1 \int_0^{x_1} dx_2 \frac{2x_2(x_2 - x_1) + x_1/2}{x_1 + zx_2(x_2 - x_1)}.\end{aligned}\quad (16)$$

From Eq. (4), it can be seen that  $Y_{1i}$  and  $Y_{2i}$  can lead to new flavor mixing effects; as a result,  $S$  can decay to the SM quarks through the tree and loop diagrams. Nevertheless, the induced vertex is suppressed by  $m_q/m_{F_i}$ , where  $m_q$  is the mass of the SM quarks. Therefore,  $S \rightarrow t\bar{t}$  is the dominant decay mode. In addition, the loop induced process has another

suppression factor  $1/(4\pi)^2$ ; therefore, the partial decay width for  $S \rightarrow t\bar{t}$  is of  $\mathcal{O}(10^{-5})$  and negligible. Hence, we show the tree-induced partial decay width for  $S \rightarrow t\bar{t}$  as:

$$\Gamma(S \rightarrow t\bar{t}) = \frac{m_S N_c}{8\pi} \lambda_{Stt}^2 \sqrt{1 - \frac{4m_t^2}{m_S^2}}, \quad (17)$$

$$\lambda_{Stt} = \frac{y_1 m_t v^2 Y_{13}^2}{4m_{F_1}^3} + \frac{y_2 m_t v^2 Y_{23}^2}{2m_{F_2}^3}.$$

In order to perform the numerical analysis, without loss of generality we set  $y_1 = y_2 = y$ ,  $m_{F_1} = m_{F_2} = m_F$ , and  $m_S = 750$  GeV. To suppress  $S$  decaying to the VLTQs, we require  $m_F > m_S$ . Thus, the main  $S$  decay modes are  $S \rightarrow f$  with  $f = gg, W^+W^-, ZZ, Z\gamma, \gamma\gamma, hh, t\bar{t}$  and the total width of the Higgs singlet is  $\Gamma_S = \sum_f \Gamma(S \rightarrow f)$ . In order to understand the total width of the Higgs singlet in the model, we present the contours for  $\Gamma_S$  as a function of  $m_F$  and  $y$  in Fig. 1, where the numbers on the plot denote the values of  $\Gamma_S$  in units of GeV and the used K-factor is  $K_{S \rightarrow gg} = 1.35$  [77]. Clearly, without fine-tuning the Yukawa coupling  $y$ , the width of the Higgs singlet is below 1 GeV. Since ATLAS and CMS do not conclude the width of the resonance, a narrow or a wide width is possible. Therefore, the diphoton resonance in our model is a narrow width scalar boson. Since loop-induced decays are all proportional to  $y$ , the BR for  $S$  decay is independent of the Yukawa coupling. Numerically, we find that the BRs for  $S \rightarrow gg/WW/ZZ/\gamma\gamma/Z\gamma/hh/t\bar{t}$  are also insensitive to the values of  $m_F$  and they are:

$$\begin{aligned} BR(S \rightarrow gg) &\approx 0.673, \quad BR(S \rightarrow W^+W^-) \approx 0.151, \\ BR(S \rightarrow ZZ) &\approx 0.095, \quad BR(S \rightarrow Z\gamma) \approx 0.039, \\ BR(S \rightarrow \gamma\gamma) &\approx 0.0170, \quad BR(S \rightarrow hh) \approx 0.007, \quad BR(S \rightarrow t\bar{t}) \approx 0.018, \end{aligned} \quad (18)$$

where  $Y_{i2,i3} = 1$  in  $\lambda_{Shh}$  have been applied.

In order to estimate the  $S$  production cross section in  $pp$  collisions at  $\sqrt{s} = 13$  TeV, we implement the effective interaction of Eq. (9) to the CalcHEP [78]. We display  $\sigma(pp \rightarrow S)$  as a function of  $y$  with  $m_F = 1$  TeV in the left panel of Fig. 2, where CTEQ6L PDF [79] is used and the K-factor is taken as  $K_{gg \rightarrow S} = 2$  [77]; in the right panel, we plot  $\sigma(pp \rightarrow S)$  as a function of  $m_F$  with  $y = 3$ . It can be seen that the  $S$  production cross section in pb can be achieved with that  $m_F$  is at TeV scale. Combined the results of  $\sigma(pp \rightarrow S)$  with those of  $BR(S \rightarrow \gamma\gamma)$ , we show the contours for  $S$  production cross section times the BR for  $S \rightarrow \gamma\gamma$  as a function of  $m_F$  and  $y$  in Fig. 3. From the plot, it is clear that with  $y \sim \mathcal{O}(1)$  and



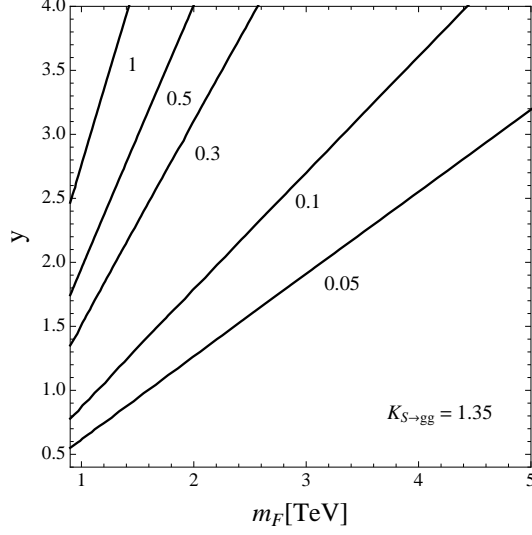


FIG. 1: Width of  $S$  ( in units of GeV) as a function of  $m_F$  and  $y$ .

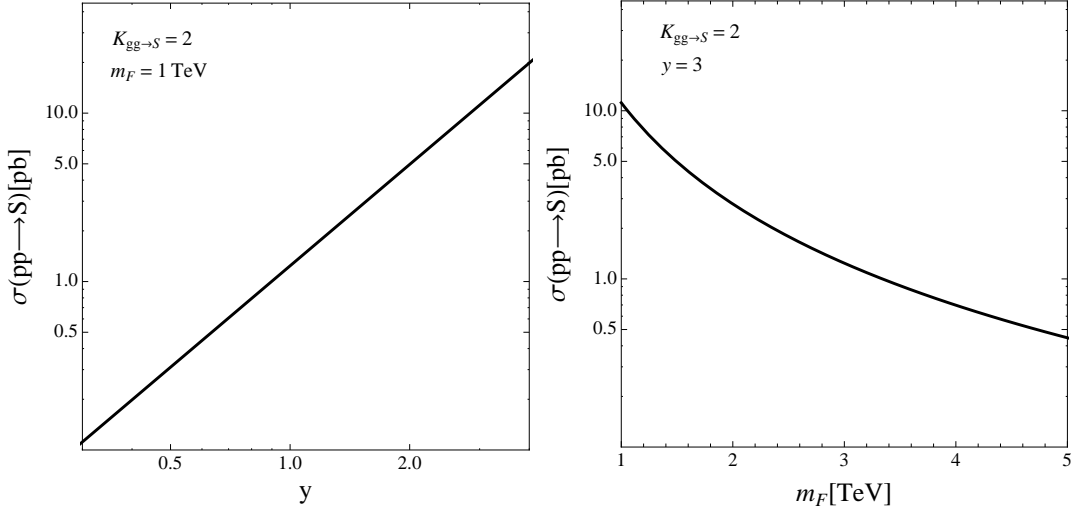


FIG. 2: Higgs singlet production cross section (in units of pb) as a function of  $y$  [left] and  $m_F$  [right], where the K-factor is taken as  $K_{gg \rightarrow S} = 2$ .

$m_F \sim O(1)$  TeV, the diphoton production cross section can match with the LHC diphoton excess.

It is interesting to see if the bounds from other experimental upper limits can be satisfied when the values of parameters are fixed by the data of diphoton excess. For performing such calculations, we require  $\sigma(gg \rightarrow S \rightarrow \gamma\gamma) \approx 6$  fb at  $\sqrt{s} = 13$  TeV, which has combined the

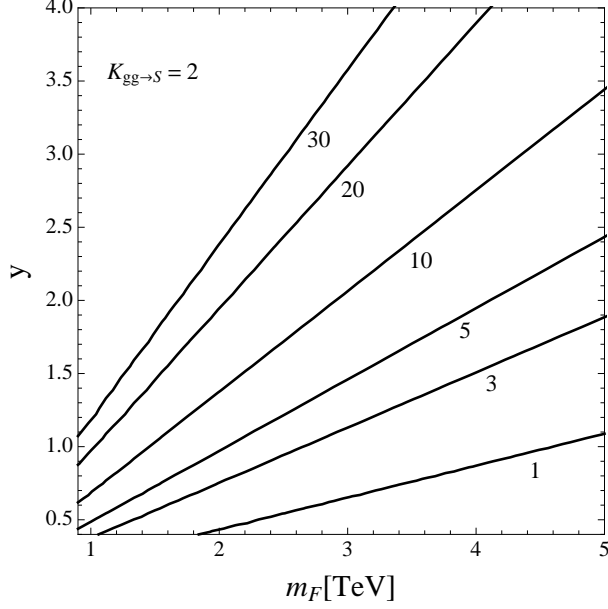


FIG. 3: Contours for  $\sigma(pp \rightarrow S) \times BR(S \rightarrow \gamma\gamma)$  as a function of  $m_F$  and  $y$ , where the numbers on the plot are in units of fb.

results of ATLAS and CMS [15, 19]. Since the experimental upper bounds are measured at  $\sqrt{s} = 8$  TeV, in order to get the theoretical results at  $\sqrt{s} = 8$  TeV, we simply divide the results at  $\sqrt{s} = 13$  TeV by the parton luminosity ratio  $\sigma(gg \rightarrow S)_{13\text{TeV}}/\sigma(gg \rightarrow S)_{8\text{TeV}} \approx 5$  [15]. We present the results at  $\sqrt{s} = 8$  and 13 TeV in Table I. It can be seen that our results are well below the experimental bounds. It is worth mentioning that besides the  $\gamma\gamma$  mode, from the table we see that the predicted  $Z\gamma$  mode is very close to the current experimental bound. It can be a good candidate to test our model.

### B. Top FCNCs, $h \rightarrow \gamma\gamma$ , and collider signatures

We discuss other interesting processes in the model below. From Eq. (4), it can be seen that after EWSB, the FCNC interactions are induced as:

$$\begin{aligned} \mathcal{L}_{hQq} = & \frac{Y_{1i}}{\sqrt{2}}(v+h) \left( \frac{1}{\sqrt{2}}\bar{u}_{Li}U_{1R} + \bar{d}_{Li}D_{1R} \right) \\ & + \frac{Y_{2i}}{\sqrt{2}}(v+h) \left( \bar{u}_{Li}U_{2R} - \frac{1}{\sqrt{2}}\bar{d}_{Li}D_{2R} \right). \end{aligned} \quad (19)$$

Final sates	Constraints(8 TeV)	Our model (8 TeV)	Our model (13 TeV)
$\gamma\gamma$	$< 1.5 \text{ fb}$ [80, 81]	1.2 fb	6 fb
$W^+W^-$	$< 40 \text{ fb}$ [82, 83]	11 fb	53 fb
$ZZ$	$< 12 \text{ fb}$ [84]	6.7 fb	34 fb
$Z\gamma$	$< 4.0 \text{ fb}$ [85]	2.8 fb	14 fb
$jj$	$\lesssim 2.5 \text{ pb}$ [86]	47 fb	237 fb
$hh$	$< 39 \text{ fb}$ [87]	0.49 fb	2.5 fb
$t\bar{t}$	$< 550 \text{ fb}$ [88]	1.3 fb	6.4 fb

TABLE I: Comparisons of our results at  $\sqrt{s} = 8$  and 13 TeV with the experimental bounds at  $\sqrt{s} = 8$  TeV, where the parton luminosity ratio  $\sigma(gg \rightarrow S)_{13\text{TeV}}/\sigma(gg \rightarrow S)_{8\text{TeV}} \approx 5$  [15] has been applied and  $\sigma(pp \rightarrow S \rightarrow \gamma\gamma) \approx 6 \text{ fb}$  is determined by the combination of ATLAS and CMS data at  $\sqrt{s} = 13 \text{ TeV}$  [15, 19].

Since the  $D - \bar{D}$ ,  $K - \bar{K}$ , and  $B_d - \bar{B}_d$  mixings make strict constraints on  $Y_{i1}$ , the related effects are small. In the numerical analysis, we ignore their contributions. We find that the FCNC interaction  $hbs$  has a strong correlation to that  $htc$  and can be written as:

$$\begin{aligned}\mathcal{L} &= -C_{sb}\bar{s}P_Rbh - \frac{m_t}{m_b}C_{sb}\bar{c}P_Rth + H.c., \\ C_{sb} &= \frac{m_b}{4v}(2\zeta_{12}\zeta_{13} + \zeta_{22}\zeta_{23})\end{aligned}\tag{20}$$

with  $\zeta_{ij} = Y_{ij}v/m_{F_i}$ . With  $\Delta m_{B_s} = 1.1688 \times 10^{-11} \text{ GeV}$ ,  $f_{B_s} = 0.224 \text{ GeV}$ ,  $m_{B_s(b)} = 5.367(4.6) \text{ GeV}$  [89], the parameter  $C_{sb}$  can be bounded as  $|C_{sb}| < 5.2 \times 10^{-4}$ . If we take  $\zeta_{12} \sim \zeta_{13} \sim \zeta_{22} \sim \zeta_{23} = \zeta$ , roughly it can be seen  $\zeta^2 < 0.036$ . Using the coupling of  $htc$  in Eq. (20), the decay rate for  $t \rightarrow ch$  process is given by:

$$\Gamma(t \rightarrow ch) = \frac{m_t}{32\pi} \left| \frac{m_t}{m_b} C_{bs} \right|^2 \left( 1 - \frac{m_h^2}{m_t^2} \right)^2.\tag{21}$$

With the width of top quark  $\Gamma_t = 1.41 \text{ GeV}$  [89] and the bound of  $C_{sb}$ , we get:

$$BR(t \rightarrow ch) < 1.1 \times 10^{-4},\tag{22}$$

where the current upper limits from ATLAS and CMS are 0.46% [90] and 0.56% [91], respectively. With a luminosity of  $\text{ab}^{-1}$  at 14 TeV, ATLAS estimates that the expected upper limit at the 95% confidence level on the BR for  $t \rightarrow ch$  decay can reach  $1.5 \times 10^{-4}$  [92].

Due to the flavor mixing effects  $Y_{1j}$  and  $Y_{2j}$ , the VLTQ loops can also contribute to the SM Higgs production cross section  $\sigma(gg \rightarrow h)$  and the SM Higgs decay  $BR(h \rightarrow gg/\gamma\gamma/Z\gamma)$ . For illustrating the influence of VLTQs, we present the ratio of our model to the SM prediction for  $pp \rightarrow h \rightarrow \gamma\gamma$  to be:

$$\begin{aligned}\mu_{\gamma\gamma} &= \frac{\sigma(pp \rightarrow h)_{\text{VLTQ}}}{\sigma(pp \rightarrow h)_{\text{SM}}} \frac{BR(h \rightarrow \gamma\gamma)_{\text{VLTQ}}}{BR(h \rightarrow \gamma\gamma)_{\text{SM}}} \\ &\approx \left| 1 + \frac{3}{4}\zeta_{gg} \right|^2 \left| 1 + \frac{N_c A_{1/2}(x_F)\zeta_{\gamma\gamma}}{A_1(x_W) + 4/3 A_{1/2}(x_t)} \right|^2,\end{aligned}\quad (23)$$

where we have adopted the limit  $m_t, m_F \gg m_h$ ,  $x_W = 4m_W^2/m_h^2$ ,  $x_t = 4m_t^2/m_h^2$ ,  $x_F = 4m_F^2/m_h^2$ ,  $A_1(x_W) \approx -8.3$ ,  $A_{1/2}(x_t) \approx 1.38$ ,

$$\begin{aligned}\zeta_{gg} &= \zeta_{12}^2 + \zeta_{13}^2 + \zeta_{22}^2 + \zeta_{23}^2, \\ \zeta_{\gamma\gamma} &= \frac{Q_u^2 + 2Q_d^2}{4}(\zeta_{12}^2 + \zeta_{13}^2) + \frac{2Q_u^2 + Q_d^2}{4}(\zeta_{22}^2 + \zeta_{23}^2),\end{aligned}\quad (24)$$

$Q_u = 2/3$ , and  $Q_d = -1/3$ . Using  $\zeta_{ij}^2 \sim \zeta^2 < 0.036$ , we get  $\mu_{\gamma\gamma} < 1.18$ , where the contribution from VLTQs to  $h \rightarrow \gamma\gamma$  is only 4%. The result is consistent with ATLAS of  $\mu_{\gamma\gamma} = 1.17 \pm 0.27$  [93] and CMS of  $\mu_{\gamma\gamma} = 1.13 \pm 0.24$  [94].

We make some remarks on the constraints from the electroweak precision measurements, such as the SM CKM matrix,  $R_b$ , and  $R_c$ . With the new Yukawa couplings in Eq. (4), the  $3 \times 3$  SM CKM matrix will be modified to be [76]:

$$(V_{\text{CKM}}^{\text{SM}})_{ij} \rightarrow (V_{\text{CKM}})_{ij} + \frac{1}{2\sqrt{2}} (\zeta_{1i}\zeta_{1j} - \zeta_{2i}\zeta_{2j}). \quad (25)$$

The modification will be smeared out if one takes  $\zeta_{1i} \approx \zeta_{2i}$ . Due to the new flavor mixing effects, the  $Z$  couplings to the SM quarks are also modified; therefore, the constraints from the electroweak precision measurements should be taken into account. Following Eqs. (8) and (19), the new  $Z$  couplings to the SM quarks are given by [76]:

$$\mathcal{L}_{Zq_i q_j} = -\frac{g}{8c_W} (a_q \zeta_{1i}\zeta_{1j} - b_q \zeta_{2i}\zeta_{2j}) \bar{q}_{iL} \gamma^\mu q_{jL} Z_\mu, \quad (26)$$

where  $q_i$  denote the up- or down-type SM quarks,  $a_u = b_d = 1$ ,  $b_u = a_d = \sqrt{2}$ , and only left-handed couplings are modified. With the scenario  $\zeta_{i2} \approx \zeta_{i3}$ , it can be seen that the changes of  $Zc\bar{c}$  and  $Zb\bar{b}$  couplings are the same in magnitude; here, we just examine the constraint from  $R_b$ . Using the results [71, 95], we write

$$\begin{aligned}R_b &= R_b^{\text{SM}}(1 - 3.56\delta g_L^b), \\ \delta g_L^b &= \frac{1}{8} \left( \sqrt{2}\zeta_{13}^2 - \zeta_{23}^2 \right).\end{aligned}\quad (27)$$

With  $R_b^{\text{exp}} = 0.21629 \pm 0.00066$  [89] and  $R_b^{\text{SM}} = 0.21474$  [96], the allowed range in  $2\sigma$  errors of data for  $\zeta_{13}^2 \approx \zeta_{23}^2 = \zeta^2$  is  $\zeta^2 \leq 0.066$ . The constraint is close to that from  $B_s$  mixing.

Finally, we discuss the possible interesting signatures at the LHC. In the model, we introduce two top partners  $U_{1,2}$ , two bottom partners  $D_{1,2}$ , and two exotic quarks  $X$  and  $Y$  with the electric charges of  $5/3$  and  $-4/3$ , respectively. The detailed studies of  $U_{1,2}$  and  $D_{1,2}$  can be referred to [71–73]; here we simply show what we find about the search for  $X$  and  $Y$ . By using the CalcHEP, the pair production cross sections for  $X$  and  $Y$  with  $m_X = m_Y = 1$  TeV at  $\sqrt{s} = 13$  TeV are 22 fb; however, the single production cross sections of  $X$  and  $\bar{Y}$  by  $W$ -mediation can reach 100 fb when  $\zeta = 0.2$  is applied. With the scenario  $\zeta_{12} \approx \zeta_{13} \approx \zeta_{22} \approx \zeta_{23}$ , the main decay channels for  $X$  and  $Y$  in turn are  $X \rightarrow W^+(t, c)$  and  $\bar{Y} \rightarrow W^+(\bar{s}, \bar{b})$  and each branching ratio is almost equal to  $1/2$ . Hence, the favorable channels to search for the single production of VLQs  $X$  and  $Y$  are

$$\begin{aligned} pp &\rightarrow dX_{5/3} \rightarrow dW^+c, \\ pp &\rightarrow dX_{5/3} \rightarrow dW^+t \rightarrow dW^+(W^+b), \\ pp &\rightarrow dY_{4/3} \rightarrow dW^+(\bar{s}, \bar{b}), \end{aligned} \tag{28}$$

where the cross sections can be 50 fb. The detailed analysis and event simulations will be studied elsewhere.

#### IV. CONCLUSION

We employed a Higgs singlet  $S$  to resolve the diphoton resonance with a mass of around 750 GeV, which is indicated by the ATLAS and CMS experiments when they analyzed the data from run 2 of the LHC at  $\sqrt{s} = 13$  TeV. In order to study the Higgs singlet production and decays, we embedded it to the VLQ model. Using the enhanced number of VLQs and new Yukawa couplings, we found that the  $S$  production cross section can be of the order of 1 pb; the BR for  $S \rightarrow \gamma\gamma$  is 0.017 and is insensitive to new Yukawa couplings and masses of VLQs. As a result,  $\sigma(pp \rightarrow S) \times BR(S \rightarrow \gamma\gamma)$  can match with the results of 3-10 fb, which are measured by the ATLAS and CMS experiments. The width of the proposed Higgs singlet is below a few GeV; therefore our model is suitable for the analysis with the narrow width approximation.

We studied the implication on the FCNC process  $t \rightarrow ch$  and found that

$BR(t \rightarrow ch) < 1.1 \times 10^{-4}$  when the data of  $B_s$  oscillation were included; with the same constrained value from  $B_s$  mixing, we demonstrated that the signal strength for diphoton channel is  $\mu_{\gamma\gamma} < 1.18$  and consistent with the current measurements in the ATLAS and CMS experiments. We examined the constraint from the precision measurement of  $Z \rightarrow b\bar{b}$  and the result is close to that from  $B_s$  mixing. It is found that the single production cross sections for VLQs  $X$  and  $\bar{Y}$  can be over 100 fb and the dominant decay channels are  $X \rightarrow W^+(c, t)$  and  $\bar{Y} \rightarrow W^+(\bar{s}, \bar{b})$ .

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- [1] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **716**, 1 (2012) [arXiv:1207.7214 [hep-ex]].
  - [2] S. Chatrchyan *et al.* [CMS Collaboration], the LHC", Phys. Lett. B **716**, 30 (2012) [arXiv:1207.7235 [hep-ex]].
  - [3] The ATLAS collaboration, ATLAS-CONF-2015-081.
  - [4] CMS Collaboration [CMS Collaboration], CMS-PAS-EXO-15-004.
  - [5] G. Aad *et al.* [ATLAS Collaboration], Phys. Rev. Lett. **113**, 171801 (2014) [arXiv:1407.6583 [hep-ex]].
  - [6] V. Khachatryan *et al.* [CMS Collaboration], Phys. Lett. B **750**, 494 (2015) [arXiv:1506.02301 [hep-ex]].
  - [7] K. Harigaya and Y. Nomura, arXiv:1512.04850 [hep-ph].
  - [8] Y. Mambrini, G. Arcadi and A. Djouadi, arXiv:1512.04913 [hep-ph].
  - [9] M. Backovic, A. Mariotti and D. Redigolo, arXiv:1512.04917 [hep-ph].
  - [10] A. Angelescu, A. Djouadi and G. Moreau, arXiv:1512.04921 [hep-ph].

- [11] Y. Nakai, R. Sato and K. Tobioka, arXiv:1512.04924 [hep-ph].
- [12] S. Knapen, T. Melia, M. Papucci and K. Zurek, arXiv:1512.04928 [hep-ph].
- [13] D. Buttazzo, A. Greljo and D. Marzocca, arXiv:1512.04929 [hep-ph].
- [14] A. Pilaftsis, arXiv:1512.04931 [hep-ph].
- [15] R. Franceschini *et al.*, arXiv:1512.04933 [hep-ph].
- [16] S. Di Chiara, L. Marzola and M. Raidal, arXiv:1512.04939 [hep-ph].
- [17] T. Higaki, K. S. Jeong, N. Kitajima and F. Takahashi, arXiv:1512.05295 [hep-ph].
- [18] S. D. McDermott, P. Meade and H. Ramani, arXiv:1512.05326 [hep-ph].
- [19] J. Ellis, S. A. R. Ellis, J. Quevillon, V. Sanz and T. You, arXiv:1512.05327 [hep-ph].
- [20] M. Low, A. Tesi and L. T. Wang, arXiv:1512.05328 [hep-ph].
- [21] B. Bellazzini, R. Franceschini, F. Sala and J. Serra, arXiv:1512.05330 [hep-ph].
- [22] R. S. Gupta, S. Jger, Y. Kats, G. Perez and E. Stamou, arXiv:1512.05332 [hep-ph].
- [23] C. Petersson and R. Torre, arXiv:1512.05333 [hep-ph].
- [24] E. Molinaro, F. Sannino and N. Vignaroli, arXiv:1512.05334 [hep-ph].
- [25] B. Dutta, Y. Gao, T. Ghosh, I. Gogoladze and T. Li, arXiv:1512.05439 [hep-ph].
- [26] Q. H. Cao, Y. Liu, K. P. Xie, B. Yan and D. M. Zhang, arXiv:1512.05542 [hep-ph].
- [27] S. Matsuzaki and K. Yamawaki, arXiv:1512.05564 [hep-ph].
- [28] A. Kobakhidze, F. Wang, L. Wu, J. M. Yang and M. Zhang, arXiv:1512.05585 [hep-ph].
- [29] R. Martinez, F. Ochoa and C. F. Sierra, arXiv:1512.05617 [hep-ph].
- [30] P. Cox, A. D. Medina, T. S. Ray and A. Spray, arXiv:1512.05618 [hep-ph].
- [31] D. Becirevic, E. Bertuzzo, O. Sumensari and R. Z. Funchal, arXiv:1512.05623 [hep-ph].
- [32] J. M. No, V. Sanz and J. Setford, arXiv:1512.05700 [hep-ph].
- [33] S. V. Demidov and D. S. Gorbunov, arXiv:1512.05723 [hep-ph].
- [34] S. Gopalakrishna, T. S. Mukherjee and S. Sadhukhan, arXiv:1512.05731 [hep-ph].
- [35] W. Chao, R. Huo and J. H. Yu, arXiv:1512.05738 [hep-ph].
- [36] S. Fichet, G. von Gersdorff and C. Royon, arXiv:1512.05751 [hep-ph].
- [37] D. Curtin and C. B. Verhaaren, arXiv:1512.05753 [hep-ph].
- [38] L. Bian, N. Chen, D. Liu and J. Shu, arXiv:1512.05759 [hep-ph].
- [39] J. Chakraborty, A. Choudhury, P. Ghosh, S. Mondal and T. Srivastava, arXiv:1512.05767 [hep-ph].
- [40] A. Ahmed, B. M. Dillon, B. Grzadkowski, J. F. Gunion and Y. Jiang, arXiv:1512.05771 [hep-

- ph].
- [41] P. Agrawal, J. Fan, B. Heidenreich, M. Reece and M. Strassler, arXiv:1512.05775 [hep-ph].
  - [42] “The Minimal Model of a Diphoton Resonance: Production without Gluon Couplings,” arXiv:1512.05776 [hep-ph].
  - [43] A. Falkowski, O. Slone and T. Volansky, arXiv:1512.05777 [hep-ph].
  - [44] D. Aloni, K. Blum, A. Dery, A. Efrati and Y. Nir, arXiv:1512.05778 [hep-ph].
  - [45] Y. Bai, J. Berger and R. Lu, arXiv:1512.05779 [hep-ph].
  - [46] N. Arkani-Hamed, A. G. Cohen, E. Katz and A. E. Nelson, JHEP **0207**, 034 (2002) [hep-ph/0206021].
  - [47] T. Han, H. E. Logan, B. McElrath and L. T. Wang, Phys. Rev. D **67**, 095004 (2003) [hep-ph/0301040].
  - [48] M. Perelstein, M. E. Peskin and A. Pierce, Phys. Rev. D **69**, 075002 (2004) [hep-ph/0310039].
  - [49] M. Schmaltz and D. Tucker-Smith, Ann. Rev. Nucl. Part. Sci. **55**, 229 (2005) [hep-ph/0502182].
  - [50] D. B. Kaplan, H. Georgi and S. Dimopoulos, Phys. Lett. B **136**, 187 (1984).
  - [51] K. Agashe, R. Contino and A. Pomarol, Nucl. Phys. B **719**, 165 (2005) [hep-ph/0412089].
  - [52] R. Contino, T. Kramer, M. Son and R. Sundrum, JHEP **0705**, 074 (2007) [hep-ph/0612180].
  - [53] C. Anastasiou, E. Furlan and J. Santiago, Phys. Rev. D **79**, 075003 (2009) [arXiv:0901.2117 [hep-ph]].
  - [54] N. Vignaroli, JHEP **1207**, 158 (2012) [arXiv:1204.0468 [hep-ph]].
  - [55] I. Antoniadis, K. Benakli and M. Quiros, New J. Phys. **3**, 20 (2001) [hep-th/0108005].
  - [56] Y. Hosotani, S. Noda and K. Takenaga, Phys. Lett. B **607**, 276 (2005) [hep-ph/0410193].
  - [57] T. Moroi and Y. Okada, Mod. Phys. Lett. A **7**, 187 (1992).
  - [58] T. Moroi and Y. Okada, Phys. Lett. B **295**, 73 (1992).
  - [59] K. S. Babu, I. Gogoladze, M. U. Rehman and Q. Shafi, Phys. Rev. D **78**, 055017 (2008) [arXiv:0807.3055 [hep-ph]].
  - [60] S. P. Martin, Phys. Rev. D **81**, 035004 (2010) [arXiv:0910.2732 [hep-ph]].
  - [61] P. W. Graham, A. Ismail, S. Rajendran and P. Saraswat, Phys. Rev. D **81**, 055016 (2010) [arXiv:0910.3020 [hep-ph]].
  - [62] S. P. Martin, Phys. Rev. D **82**, 055019 (2010) [arXiv:1006.4186 [hep-ph]].
  - [63] S. Heinemeyer *et al.* [LHC Higgs Cross Section Working Group Collaboration],



- doi:10.5170/CERN-2013-004 arXiv:1307.1347 [hep-ph].
- [64] J. F. Gunion, H. E. Haber, G. L. Kane and S. Dawson, *Front. Phys.* **80**, 1 (2000).
  - [65] D. Carmi, A. Falkowski, E. Kuflik and T. Volansky, *JHEP* **1207**, 136 (2012) doi:10.1007/JHEP07(2012)136 [arXiv:1202.3144 [hep-ph]].
  - [66] D. Carmi, A. Falkowski, E. Kuflik, T. Volansky and J. Zupan, *JHEP* **1210**, 196 (2012) doi:10.1007/JHEP10(2012)196 [arXiv:1207.1718 [hep-ph]].
  - [67] J. Jaeckel, M. Jankowiak and M. Spannowsky, *Phys. Dark Univ.* **2**, 111 (2013) [arXiv:1212.3620 [hep-ph]].
  - [68] F. del Aguila, M. Perez-Victoria and J. Santiago, *JHEP* **0009**, 011 (2000) [hep-ph/0007316].
  - [69] Y. Okada and L. Panizzi, *Adv. High Energy Phys.* **2013**, 364936 (2013) [arXiv:1207.5607 [hep-ph]].
  - [70] G. Cacciapaglia, A. Deandrea, L. Panizzi, S. Perries and V. Sordini, *JHEP* **1303**, 004 (2013) [arXiv:1211.4034 [hep-ph]].
  - [71] J. A. Aguilar-Saavedra, R. Benbrik, S. Heinemeyer and M. Perez-Victoria, *Phys. Rev. D* **88**, no. 9, 094010 (2013) [arXiv:1306.0572 [hep-ph]].
  - [72] S. Gopalakrishna, T. Mandal, S. Mitra and G. Moreau, *JHEP* **1408**, 079 (2014) [arXiv:1306.2656 [hep-ph]].
  - [73] D. Karabacak, S. Nandi and S. K. Rai, *Phys. Lett. B* **737**, 341 (2014) [arXiv:1405.0476 [hep-ph]].
  - [74] J. de Blas, M. Chala, M. Perez-Victoria and J. Santiago, *JHEP* **1504**, 078 (2015) [arXiv:1412.8480 [hep-ph]].
  - [75] G. Cacciapaglia, A. Deandrea, N. Gaur, D. Harada, Y. Okada and L. Panizzi, arXiv:1502.00370 [hep-ph].
  - [76] C. H. Chen and T. Nomura, *Phys. Rev. D* **92**, no. 11, 115021 (2015) [arXiv:1509.02039 [hep-ph]].
  - [77] A. Djouadi, *Phys. Rept.* **457**, 1 (2008) [hep-ph/0503172].
  - [78] A. Belyaev, N. D. Christensen and A. Pukhov, *Comput. Phys. Commun.* **184**, 1729 (2013) [arXiv:1207.6082 [hep-ph]].
  - [79] P. M. Nadolsky, H. L. Lai, Q. H. Cao, J. Huston, J. Pumplin, D. Stump, W. K. Tung and C.-P. Yuan, *Phys. Rev. D* **78**, 013004 (2008) [arXiv:0802.0007 [hep-ph]].
  - [80] CMS Collaboration [CMS Collaboration], CMS-PAS-HIG-14-006.

- [81] G. Aad *et al.* [ATLAS Collaboration], Phys. Rev. D **92**, no. 3, 032004 (2015) [arXiv:1504.05511 [hep-ex]].
- [82] V. Khachatryan *et al.* [CMS Collaboration], JHEP **1510**, 144 (2015) [arXiv:1504.00936 [hep-ex]].
- [83] G. Aad *et al.* [ATLAS Collaboration], JHEP **1601**, 032 (2016) [arXiv:1509.00389 [hep-ex]].
- [84] G. Aad *et al.* [ATLAS Collaboration], Eur. Phys. J. C **76**, no. 1, 45 (2016) [arXiv:1507.05930 [hep-ex]].
- [85] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **738**, 428 (2014) [arXiv:1407.8150 [hep-ex]].
- [86] G. Aad *et al.* [ATLAS Collaboration], Phys. Rev. D **91**, no. 5, 052007 (2015) [arXiv:1407.1376 [hep-ex]].
- [87] The ATLAS collaboration [ATLAS Collaboration], ATLAS-CONF-2014-005.
- [88] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Rev. Lett. **111** (2013) 21, 211804 [Phys. Rev. Lett. **112** (2014) 11, 119903] [arXiv:1309.2030 [hep-ex]].
- [89] K. A. Olive *et al.* (Particle Data Group), Chin. Phys. C, 38, 090001 (2014).
- [90] G. Aad *et al.* [ATLAS Collaboration], arXiv:1509.06047 [hep-ex].
- [91] CMS Collaboration, CMS-PAS-HIG-13-034 (2014).
- [92] ATLAS Collaboration, ATL-PHYS-PUB-2013-012.
- [93] G. Aad *et al.* [ATLAS Collaboration], arXiv:1507.04548 [hep-ex].
- [94] S. Chatrchyan *et al.* [CMS Collaboration], CMS-PAS-HIG-14-009.
- [95] P. Bamert, C. P. Burgess, J. M. Cline, D. London and E. Nardi, Phys. Rev. D **54**, 4275 (1996) doi:10.1103/PhysRevD.54.4275 [hep-ph/9602438].
- [96] M. Baak *et al.*, Eur. Phys. J. C **72**, 2205 (2012) doi:10.1140/epjc/s10052-012-2205-9 [arXiv:1209.2716 [hep-ph]].